

**APPLICATION FOR UNITED STATES LETTERS PATENT**

**for**

**SINGLE CHAMBER COMPACT FUEL PROCESSOR**

**by**

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## BACKGROUND OF THE INVENTION

Fuel cells provide electricity from chemical oxidation-reduction reactions and possess significant advantages over other forms of power generation in terms of cleanliness and efficiency. Typically, fuel cells employ hydrogen as the fuel and oxygen as the oxidizing agent. The power generation is proportional to the consumption rate of the reactants.

A significant disadvantage that inhibits the wider use of fuel cells is the lack of a widespread hydrogen infrastructure. Hydrogen has a relatively low volumetric energy density and is more difficult to store and transport than the hydrocarbon fuels currently used in most power generation systems. One way to overcome this difficulty is the use of reformers to convert the hydrocarbons to a hydrogen rich gas stream which can be used as a feed for fuel cells.

Hydrocarbon-based fuels, such as natural gas, LPG, gasoline, and diesel, require conversion processes to be used as fuel sources for most fuel cells. Current art uses multi-step processes combining an initial conversion process with several clean-up processes. The initial process is most often steam reforming (SR), autothermal reforming (ATR), catalytic partial oxidation (CPOX), or non-catalytic partial oxidation (POX). The clean-up processes are usually comprised of a combination of desulfurization, high temperature water-gas shift, low temperature water-gas shift, selective CO oxidation, or selective CO methanation. Alternative processes include hydrogen selective membrane reactors and filters.

Despite the above work, there remains a need for a simple unit for converting a hydrocarbon fuel to a hydrogen rich gas stream for use in conjunction with a fuel cell.

## SUMMARY OF THE INVENTION

The present invention is generally directed to an apparatus and method for converting hydrocarbon fuel into a hydrogen rich gas. In one illustrative embodiment of the present invention, a compact fuel processor for converting a hydrocarbon fuel feed into hydrogen rich gas, in which the fuel processor assembly includes a cylinder having an inlet end and an outlet end, wherein the cylinder is loaded with a plurality of catalysts in series fashion thus forming a series of reaction zones; and a heat exchanger having an

1 inlet end and an outlet end, wherein the heat exchanger is internally positioned through  
2 the length of the cylinder so as to provide heat or remove heat as required by a particular  
3 reaction zone. Within such an illustrative embodiment, the plurality of catalysts includes  
4 autothermal reforming catalyst, desulfurization catalyst, water gas shift catalyst,  
5 preferential oxidation catalyst, and mixtures and combinations of these and similar  
6 catalysts. The hydrocarbon fuel feed utilized in the illustrative fuel processor is  
7 preheated, preferably by passing through the heat exchanger prior to being introduced to  
8 the cylinder or alternatively by a fuel pre-heater located in a function upstream position  
9 from the autothermal reforming reaction zone. A wide variety of hydrocarbon fuels may  
10 be utilized, however, in one illustrative embodiment the hydrocarbon fuel is selected  
11 from natural gas, gasoline, diesel, fuel oil, propane, liquefied petroleum, methanol,  
12 ethanol or other similar and suitable hydrocarbons and mixtures of these.

13 One of skill in the art should also understand and appreciate that another  
14 illustrative embodiment of the present invention includes a compact fuel processor for  
15 converting a hydrocarbon fuel feed to hydrogen rich gas, that is composed of a reaction  
16 chamber; a plurality of predefined reaction zones within said reaction chamber, wherein  
17 each reaction zone is characterized by the chemical reaction that takes place within the  
18 reaction zone.; and a heat exchanger having an inlet end and an outlet end, wherein the  
19 heat exchanger is positioned at least partially within the reaction chamber. In one such  
20 illustrative embodiment, a first reaction zone contains autothermal reforming catalyst, a  
21 second reaction zone contains desulfurization catalyst, a third reaction zone contains  
22 water gas shift catalyst, and a reaction zone module contains preferential oxidation  
23 catalyst. When considering such an illustrative embodiment, it is contemplated that the  
24 heat exchanger is not substantially positioned within the first reaction zone. The  
25 hydrocarbon fuel feed for one illustrative embodiment is preheated by passing through  
26 the heat exchanger prior to being introduced to the reaction chamber. Alternatively, the  
27 mixture of hydrocarbon fuel feed, air, and water is preheated by passing through the heat  
28 exchanger prior to being introduced to the first reaction zone. A wide variety of  
29 hydrocarbon fuels as noted above may be utilized.

30 It should be appreciated a by one of skill in the art that each reaction zone of the  
31 plurality of reaction zones may contain one or more catalysts. In one such illustrative

1 embodiment, the catalysts are selected from autothermal reforming catalyst,  
2 desulfurization catalyst, water gas shift catalyst, preferential oxidation catalyst as well as  
3 mixtures and combinations of these and similar catalysts. Any particular reaction zone  
4 containing more than one catalyst may be separated from an adjacent reaction zone by a  
5 permeable plate that also serves to support the adjacent reaction zones. In one illustrative  
6 embodiment, the plate is selected from perforated metal, metal screen, metal mesh,  
7 sintered metal, porous ceramic, or combinations of these materials and similar materials.  
8 It is preferred within such an illustrative embodiment that the plate be at least partially  
9 composed of inconel, carbon steel, and stainless steel.

10 The present invention also includes a process for converting hydrocarbon fuel into  
11 a hydrogen rich gas. One such illustrative process utilizes the apparatus disclosed herein.  
12 Such a process generally includes providing a fuel processor having a reactor chamber in  
13 which a plurality of catalysts have been loaded. The flow of the reactant gas through the  
14 reactor chamber is such that each area of the reaction chamber forms series of discrete  
15 reaction zone. By feeding the hydrocarbon fuel successively through each of the reaction  
16 zones in a predetermined manner, a hydrogen rich gas is produced in a manner that  
17 optimizes space considerations and heat transfer considerations.

## 18 19 **BRIEF DESCRIPTION OF THE DRAWINGS**

20 The description is presented with reference to the accompanying drawings in  
21 which:

22 FIG. 1 depicts a simple process flow diagram for one illustrative embodiment of  
23 the present invention.

24 FIG. 2 depicts a first illustrative embodiment of a compact fuel processor  
25 apparatus of the present invention; and

26 FIG. 3 depicts a second illustrative embodiment of a compact fuel processor  
27 apparatus of the present invention.

## 28 29 **DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS**

30 The present invention is generally directed to an apparatus for converting  
31 hydrocarbon fuel into a hydrogen rich gas. In a preferred aspect, the apparatus and

1 method described herein relate to a compact processor for producing a hydrogen rich gas  
2 stream from a hydrocarbon fuel for use in fuel cells. However, other possible uses are  
3 contemplated for the apparatus and method described herein, including any use wherein a  
4 hydrogen rich stream is desired. Accordingly, while the invention is described herein as  
5 being used in conjunction with a fuel cell, the scope of the invention is not limited to such  
6 use.

7 Each of the illustrative embodiments of the present invention describe a fuel  
8 processor or a process for using such a fuel processor with the hydrocarbon fuel feed  
9 being directed through the fuel processor. The hydrocarbon fuel may be liquid or gas at  
10 ambient conditions as long as it can be vaporized. As used herein the term  
11 "hydrocarbon" includes organic compounds having C-H bonds which are capable of  
12 producing hydrogen from a partial oxidation or steam reforming reaction. The presence  
13 of atoms other than carbon and hydrogen in the molecular structure of the compound is  
14 not excluded. Thus, suitable fuels for use in the method and apparatus disclosed herein  
15 include, but are not limited to hydrocarbon fuels such as natural gas, methane, ethane,  
16 propane, butane, naphtha, gasoline, and diesel fuel, and alcohols such as methanol,  
17 ethanol, propanol, and the like.

18 The fuel processor feeds include hydrocarbon fuel, oxygen, and water. The  
19 oxygen can be in the form of air, enriched air, or substantially pure oxygen. The water  
20 can be introduced as a liquid or vapor. The composition percentages of the feed  
21 components are determined by the desired operating conditions, as discussed below.

22 The fuel processor effluent stream from of the present invention includes  
23 hydrogen and carbon dioxide and can also include some water, unconverted  
24 hydrocarbons, carbon monoxide, impurities (e.g. hydrogen sulfide and ammonia) and  
25 inert components (e.g., nitrogen and argon, especially if air was a component of the feed  
26 stream).

27 Figure 1 depicts a general process flow diagram illustrating the process steps  
28 included in the illustrative embodiments of the present invention. One of skill in the art  
29 should appreciate that a certain amount of progressive order is needed in the flow of the  
30 reactants through the reactors disclosed herein.

1 Process step A is an autothermal reforming process in which two reactions, partial  
2 oxidation (formula I, below) and optionally also steam reforming (formula II, below), are  
3 combined to convert the feed stream F into a synthesis gas containing hydrogen and  
4 carbon monoxide. Formulas I and II are exemplary reaction formulas wherein methane is  
5 considered as the hydrocarbon:



8 The partial oxidation reaction occurs very quickly to the complete conversion of  
9 oxygen added and produces heat. The steam reforming reaction occurs slower and  
10 consumes heat. A higher concentration of oxygen in the feed stream favors partial  
11 oxidation whereas a higher concentration of water vapor favors steam reforming.  
12 Therefore, the ratios of oxygen to hydrocarbon and water to hydrocarbon become  
13 characterizing parameters. These ratios affect the operating temperature and hydrogen  
14 yield.

15 The operating temperature of the autothermal reforming step can range from  
16 about 550°C to about 900°C, depending on the feed conditions and the catalyst. The  
17 invention uses a catalyst bed of a partial oxidation catalyst with or without a steam  
18 reforming catalyst. The catalyst may be in any form including pellets, spheres, extrudate,  
19 monoliths, and the like. Partial oxidation catalysts should be well known to those with  
20 skill in the art and are often comprised of noble metals such as platinum, palladium,  
21 rhodium, and/or ruthenium on an alumina washcoat on a monolith, extrudate, pellet or  
22 other support. Non-noble metals such as nickel or cobalt have been used. Other  
23 washcoats such as titania, zirconia, silica, and magnesia have been cited in the literature.  
24 Many additional materials such as lanthanum, cerium, and potassium have been cited in  
25 the literature as "promoters" that improve the performance of the partial oxidation  
26 catalyst.

27 Steam reforming catalysts should be known to those with skill in the art and can  
28 include nickel with amounts of cobalt or a noble metal such as platinum, palladium,  
29 rhodium, ruthenium, and/or iridium. The catalyst can be supported, for example, on  
30 magnesia, alumina, silica, zirconia, or magnesium aluminate, singly or in combination.  
31 Alternatively, the steam reforming catalyst can include nickel, preferably supported on

1    magnesia, alumina, silica, zirconia, or magnesium aluminate, singly or in combination,  
2    promoted by an alkali metal such as potassium.

3            Process step B is a cooling step for cooling the synthesis gas stream from process  
4    step A to a temperature of from about 200°C to about 600°C, preferably from about  
5    300°C to about 500°C, and more preferably from about 375°C to about 425°C, to  
6    optimize the temperature of the synthesis gas effluent for the next step. This cooling may  
7    be achieved with heat sinks, heat pipes or heat exchangers depending upon the design  
8    specifications and the need to recover / recycle the heat content of the gas stream. One  
9    illustrative embodiment for step B is the use of a heat exchanger utilizing feed stream F  
10   as the coolant circulated through the heat exchanger. The heat exchanger can be of any  
11   suitable construction known to those with skill in the art including shell and tube, plate,  
12   spiral, etc. Alternatively, or in addition thereto, cooling step B may be accomplished by  
13   injecting additional feed components such as fuel, air or water. Water is preferred  
14   because of its ability to absorb a large amount of heat as it is vaporized to steam. The  
15   amounts of added components depend upon the degree of cooling desired and are readily  
16   determined by those with skill in the art.

17            Process step C is a purifying step. One of the main impurities of the hydrocarbon  
18   stream is sulfur, which is converted by the autothermal reforming step A to hydrogen  
19   sulfide. The processing core used in process step C preferably includes zinc oxide and/or  
20   other material capable of absorbing and converting hydrogen sulfide, and may include a  
21   support (e.g., monolith, extrudate, pellet etc.). Desulfurization is accomplished by  
22   converting the hydrogen sulfide to water in accordance with the following reaction  
23   formula III:



25            Other impurities such as chlorides can also be removed. The reaction is  
26   preferably carried out at a temperature of from about 300°C to about 500°C, and more  
27   preferably from about 375°C to about 425°C. Zinc oxide is an effective hydrogen sulfide  
28   absorbent over a wide range of temperatures from about 25°C to about 700°C and affords  
29   great flexibility for optimizing the sequence of processing steps by appropriate selection  
30   of operating temperature.

1       The effluent stream may then be sent to a mixing step D in which water is  
2 optionally added to the gas stream. The addition of water lowers the temperature of the  
3 reactant stream as it vaporizes and supplies more water for the water gas shift reaction of  
4 process step E (discussed below). The water vapor and other effluent stream components  
5 are mixed by being passed through a processing core of inert materials such as ceramic  
6 beads or other similar materials that effectively mix and/or assist in the vaporization of  
7 the water. Alternatively, any additional water can be introduced with feed, and the  
8 mixing step can be repositioned to provide better mixing of the oxidant gas in the CO  
9 oxidation step G disclosed below.

10       Process step E is a water gas shift reaction that converts carbon monoxide to  
11 carbon dioxide in accordance with formula IV:



13       This is an important step because carbon monoxide, in addition to being highly  
14 toxic to humans, is a poison to fuel cells. The concentration of carbon monoxide should  
15 preferably be lowered to a level that can be tolerated by fuel cells, typically below 50  
16 ppm. Generally, the water gas shift reaction can take place at temperatures of from  
17 150°C to 600°C depending on the catalyst used. Under such conditions, most of the  
18 carbon monoxide in the gas stream is converted in this step.

19       Low temperature shift catalysts operate at a range of from about 150°C to about  
20 300°C and include for example, copper oxide, or copper supported on other transition  
21 metal oxides such as zirconia, zinc supported on transition metal oxides or refractory  
22 supports such as silica, alumina, zirconia, etc., or a noble metal such as platinum,  
23 rhenium, palladium, rhodium or gold on a suitable support such as silica, alumina,  
24 zirconia, and the like.

25       High temperature shift catalysts are preferably operated at temperatures ranging  
26 from about 300° to about 600°C and can include transition metal oxides such as ferric  
27 oxide or chromic oxide, and optionally including a promoter such as copper or iron  
28 silicide. Also included, as high temperature shift catalysts are supported noble metals  
29 such as supported platinum, palladium and/or other platinum group members.

30       The processing core utilized to carry out this step can include a packed bed of  
31 high temperature or low temperature shift catalyst such as described above, or a



1 combination of both high temperature and low temperature shift catalysts. The process  
2 should be operated at any temperature suitable for the water gas shift reaction, preferably  
3 at a temperature of from 150°C to about 400°C depending on the type of catalyst used.  
4 Optionally, a cooling element such as a cooling coil may be disposed in the processing  
5 core of the shift reactor to lower the reaction temperature within the packed bed of  
6 catalyst. Lower temperatures favor the conversion of carbon monoxide to carbon  
7 dioxide. Also, a purification processing step C can be performed between high and low  
8 shift conversions by providing separate steps for high temperature and low temperature  
9 shift with a desulfurization module between the high and low temperature shift steps.

10 Process step F is a cooling step performed in one embodiment by a heat  
11 exchanger. The heat exchanger can be of any suitable construction including shell and  
12 tube, plate, spiral, etc. Alternatively a heat pipe or other form of heat sink may be  
13 utilized. The goal of the heat exchanger is to reduce the temperature of the gas stream to  
14 produce an effluent having a temperature preferably in the range of from about 90°C to  
15 about 150°C.

16 Oxygen is added to the process in step F. The oxygen is consumed by the  
17 reactions of process step G described below. The oxygen can be in the form of air,  
18 enriched air, or substantially pure oxygen. The heat exchanger may by design provide  
19 mixing of the air with the hydrogen rich gas. Alternatively, the embodiment of process  
20 step D may be used to perform the mixing.

21 Process step G is an oxidation step wherein almost all of the remaining carbon  
22 monoxide in the effluent stream is converted to carbon dioxide. The processing is carried  
23 out in the presence of a catalyst for the oxidation of carbon monoxide and may be in any  
24 suitable form, such as pellets, spheres, monolith, etc. Oxidation catalysts for carbon  
25 monoxide are known and typically include noble metals (e.g., platinum, palladium)  
26 and/or transition metals (e.g., iron, chromium, manganese), and/or compounds of noble  
27 or transition metals, particularly oxides. A preferred oxidation catalyst is platinum on an  
28 alumina washcoat. The washcoat may be applied to a monolith, extrudate, pellet or other  
29 support. Additional materials such as cerium or lanthanum may be added to improve  
30 performance. Many other formulations have been cited in the literature with some  
31 practitioners claiming superior performance from rhodium or alumina catalysts.

1 Ruthenium, palladium, gold, and other materials have been cited in the literature as being  
2 active for this use.

3 Two reactions occur in process step G: the desired oxidation of carbon monoxide  
4 (formula V) and the undesired oxidation of hydrogen (formula VI) as follows:



7 The preferential oxidation of carbon monoxide is favored by low temperatures. Since  
8 both reactions produce heat it may be advantageous to optionally include a cooling  
9 element such as a cooling coil disposed within the process. The operating temperature of  
10 process is preferably kept in the range of from about 90°C to about 150°C. Process step  
11 G preferably reduces the carbon monoxide level to less than 50 ppm, which is a suitable  
12 level for use in fuel cells, but one of skill in the art should appreciate that the present  
13 invention can be adapted to produce a hydrogen rich product with of higher and lower  
14 levels of carbon monoxide.

15 The effluent exiting the fuel processor is a hydrogen rich gas containing carbon  
16 dioxide and other constituents which may be present such as water, inert components  
17 (e.g., nitrogen, argon), residual hydrocarbon, etc. Product gas may be used as the feed for  
18 a fuel cell or for other applications where a hydrogen rich feed stream is desired.  
19 Optionally, product gas may be sent on to further processing, for example, to remove the  
20 carbon dioxide, water or other components.

21 Figure 2 depicts a cross-sectional view of a fuel processor 20 that is an illustrative  
22 embodiment of the present invention. One of ordinary skill in the art should see and  
23 appreciate that fuel or alternatively a fuel / oxygen or alternatively a fuel / oxygen / water  
24 mixture 200, is introduced to the inlet end of a coiled tubing heat exchanger 202. The  
25 heat exchanger is positioned within the fuel processor such that the heat exchanger  
26 substantially extends the length of the fuel processor. The heat exchanger pre-heats the  
27 fuel as well as cools / controls the temperature of the various reaction zones. One of skill  
28 in the art should appreciate that a number of factors effect the heat transfer process  
29 including the flow rate of fuel, the fuels heat capacity, the number of coils present in any  
30 particular reaction zone, the diameter of the tubing used to make the coils, the presence or  
31 absence of fins on the coils and so forth. However, such heat transfer considerations can

1 be optimized through routine calculations and experimentation. The preheated fuel  
2 leaves the heat exchanger and is routed to the first reaction zone 208 by a reactor feed  
3 tube 204. The reactor feed tube may include flow control devices, and the like to  
4 condition and optimize the fuel mixture prior to introduction into the first reaction zone  
5 208. The first reaction zone 208 in the present illustrative embodiment is packed with a  
6 autothermal reforming reaction catalyst. Such catalyst may be in pellet form or supported  
7 on a monolith. In some instances a distribution plate 206 may be needed to achieve an  
8 even distribution of fuel to the entire first reaction zone. Also optionally an electric pre-  
9 heater (not shown) may be utilized in the start-up of the fuel processor. After the fuel has  
10 reacted in the first reaction zone to form a hydrogen rich gas, the natural flow of the gas  
11 due to pressure is for the hydrogen rich gas to flow into the second reaction zone 210. In  
12 the present illustrative embodiment, the second reaction zone is packed with a  
13 desulfurization catalyst, preferably zinc oxide. Passage of the hydrogen rich gas over a  
14 desulfurization catalyst, such as zinc oxide, substantially reduces the concentration of  
15 sulfur containing compounds in the hydrogen rich gas stream. The desulfurized  
16 hydrogen rich gas is then passed into the 3<sup>rd</sup> reaction zone 212. The third reaction zone  
17 of the present illustrative embodiment is packed with a water-gas shift reactor catalyst or  
18 mixture of such catalyst as discussed above. The passage of the hydrogen rich gas over  
19 this catalyst further enriches the hydrogen content and reduces the carbon monoxide  
20 concentration. The hydrogen rich gas is then passed onto the fourth reaction zone 214  
21 which contains a preferential oxidation catalyst. Such a catalyst will reduce the carbon  
22 monoxide concentration to preferably less than 50 part per million as discussed above. In  
23 some instances air or another suitable oxygen source may be injected into the fourth  
24 reaction zone so that the preferential oxidation reaction is optimized. This may be  
25 accomplished by well-known means such as a simple gas injection tube (not shown)  
26 inserted into the partial oxidation catalyst bed. In one preferred embodiment porous tube  
27 is substantially incorporated into the design of the preferential oxidation reaction zone  
28 design and is designed such that an even distribution of injected oxygen is achieved. The  
29 final product is a hydrogen rich gas 216. It should also be noted that in one preferred and  
30 illustrative embodiment, an inert but porous and flexible material such as glass wool,  
31 ceramic wool, rock wool, or other similar inert material may be used in the reaction zone

1 transition regions 218. Such a material serves to aid in the packing of the reactor with the  
2 various catalysts, assists in preventing inadvertent mixing of catalysts during transport  
3 and provides a cushioning or buffer zone between each of the differing reaction zones.  
4 The hydrogen rich gas is preferably used in a fuel cell or may be stored or used in other  
5 processes that should be apparent to one of skill in the art.

6 One of skill in the art after reviewing the above description of Figure 2 should  
7 understand and appreciate that each module performs a separate operational function.  
8 Feed stream F (200) is introduced through inlet pipe (not shown) and product gas P 216 is  
9 drawn off via outlet pipe (not shown). Reaction zone 208 is the autothermal reforming  
10 reaction zone corresponding to process step A of Figure 1. An electric heater (not  
11 shown) may be installed at the bottom inlet of the reactor for start-up heat. Reaction zone  
12 210 is a purifying reaction zone corresponding to process step C of Figure 1. Reaction  
13 zone 212 is a water gas shift reaction zone corresponding to process step E of Figure 1.  
14 The cooling step corresponding to process step F of Figure 1 is carried out by a heat  
15 exchanger 202. Reaction zone 214 is an oxidation step corresponding to process step G  
16 of Figure 1. Air source (not shown) provides a source for oxygen to process gas for the  
17 oxidation reaction (Equation V) of reaction zone 214. Reaction zone 214 also contains a  
18 heat exchanger 202 positioned within or surrounding the catalyst bed so as to maintain a  
19 desired oxidation reaction temperature. One of skill in the art should appreciate that the  
20 process configuration described in this embodiment may vary depending on numerous  
21 factors, including but not limited to feedstock quality and required product quality.

22 Considering now Fig. 3 a second illustrative embodiment of the present invention  
23 is depicted showing a fuel processor reaction chamber 40 in a cross-sectional view. One  
24 of ordinary skill in the art should understand and appreciate that fuel or alternatively a  
25 fuel / oxygen or alternatively a fuel / oxygen / water mixture 300, is introduced to the  
26 inlet end of a first coiled tubing heat exchanger 302. Each of the heat exchangers (302,  
27 304, and 306) are preferably in fluid communication with each other. Each heat  
28 exchanger is positioned within the fuel processor such that the heat exchanger  
29 substantially extends the length of a particular reaction zone. The heat exchanger pre-  
30 heats the fuel as well as cools / controls the temperature of the various reaction zones.

1           One of skill in the art should appreciate that a number of factors effect the heat  
2 transfer process including the flow rate of fuel, the fuels heat capacity, the number of  
3 coils present in any particular reaction zone, the diameter of the tubing used to make the  
4 coils, the presence or absence of fins on the coils and so forth. However, such heat  
5 transfer considerations can be optimized through routine calculations and  
6 experimentation.

7           The preheated fuel leaves the heat exchanger and is routed to the first reaction  
8 zone 312 by a reactor feed tube 308. The reactor feed tube may include flow control  
9 devices, and the like to condition and optimize the fuel mixture prior to introduction into  
10 the first reaction zone 312. The first reaction zone 312 in the present illustrative  
11 embodiment is packed with a autothermal reforming reaction catalyst. Such catalyst may  
12 be in pellet form or supported on a monolith. In some instances a distribution plate 310  
13 may be needed to achieve an even distribution of fuel to the entire first reaction zone.  
14 Also optionally an electric pre-heater (not shown) may be utilized in the start-up of the  
15 fuel processor. After the fuel has reacted in the first reaction zone to form a hydrogen  
16 rich gas, the natural flow of the gas due to pressure is to flow past the first support plate  
17 314 and thus flow into the second reaction zone 316. In the present illustrative  
18 embodiment, the second reaction zone is packed with a desulfurization catalyst,  
19 preferably zinc oxide. Passage of the hydrogen rich gas over a desulfurization catalyst,  
20 such as zinc oxide, substantially reduces the concentration of sulfur containing  
21 compounds in the hydrogen rich gas stream. The temperature of the second reaction zone  
22 is at least partially controlled by the third heat exchanger 304. The desulfurized  
23 hydrogen rich gas is then passed through the second support plate 318 into the third  
24 reaction zone 320. The third reaction zone of the present illustrative embodiment is  
25 packed with a water-gas shift reactor catalyst or mixture of such catalyst as discussed  
26 above. The passage of the hydrogen rich gas over this catalyst further enriches the  
27 hydrogen content and reduces the carbon monoxide concentration. The temperature of  
28 the third reaction zone is at least partially controlled by the second heat exchanger 304.  
29 The hydrogen rich gas is then passed through the third support plate 322 and into the  
30 fourth reaction zone 324 which contains a preferential oxidation catalyst. Such a catalyst  
31 will reduce the carbon monoxide concentration to preferably less than 50 part per million

1 as discussed above. In some instances air or another suitable oxygen source may be  
2 injected into the fourth reaction zone so that the preferential oxidation reaction is  
3 optimized. This may be accomplished by well known means such as a simple gas  
4 injection tube (not show) inserted into the partial oxidation catalyst bed. In one preferred  
5 embodiment porous tube is substantially incorporated into the design of the preferential  
6 oxidation reaction zone design and is designed such that an even distribution of injected  
7 oxygen is achieved. The temperature of this fourth reaction zone is at least partially  
8 controlled by the first heat exchanger 302 which simultaneously preheats the incoming  
9 fuel and cools the final product gas exiting the reactor. The final product is a hydrogen  
10 rich gas 326. It should also be noted that each of the reaction zones in the illustrative  
11 embodiment is separated from any adjacent reaction zone by an inert but porous support  
12 plate. Such a support plate is preferably a rigid relatively unreactive under the conditions  
13 in the reactor material used in the reaction zone transition regions. Such a material serves  
14 to aid in the packing of the reactor with the various catalysts, assists in preventing  
15 inadvertent mixing of catalysts during transport and provides a cushioning or buffer zone  
16 between each of the differing reaction zones. The hydrogen rich gas is preferably used in  
17 a fuel cell or may be stored or used in other processes that should be apparent to one of  
18 skill in the art.

19 One of skill in the art after reviewing the above description of Figure 3 should  
20 understand and appreciate that each module performs a separate operational function.  
21 Feed stream F (300) is introduced through inlet pipe (not shown) and product gas P 326 is  
22 drawn off via outlet pipe (not shown). Reaction zone 312 is the autothermal reforming  
23 reaction zone corresponding to process step A of Figure 1. An electric heater (not shown)  
24 is optionally installed at the bottom of the reactor for start-up heat. Reaction zone 316 is  
25 a purifying reaction zone corresponding to process step C of Figure 1. Reaction zone 320  
26 is a water gas shift reaction zone corresponding to process step E of Figure 1. The  
27 cooling step corresponding to process step F of Figure 1 is carried out by a heat  
28 exchanger 304. Reaction zone 324 is an oxidation step corresponding to process step G  
29 of Figure 1. Air source (not shown) provides a source for oxygen to process gas for the  
30 oxidation reaction (Equation V) of reaction zone 324. Reaction zone 324 also contains a  
31 heat exchanger 320 positioned within or surrounding the catalyst bed so as to maintain a

1 desired oxidation reaction temperature. One of skill in the art should appreciate that the  
2 process configuration described in this embodiment may vary depending on numerous  
3 factors, including but not limited to feedstock quality and required product quality.

4 In view of the above disclosure, one of ordinary skill in the art should understand  
5 and appreciate that the present invention includes many possible illustrative embodiments  
6 that depend upon design criteria. One such illustrative embodiment includes a compact  
7 fuel processor for converting a hydrocarbon fuel feed into hydrogen rich gas, in which  
8 the fuel processor assembly includes a cylinder having an inlet end and an outlet end,  
9 wherein the cylinder is loaded with a plurality of catalysts in series fashion thus forming  
10 a series of reaction zones; and a heat exchanger having an inlet end and an outlet end,  
11 wherein the heat exchanger is internally positioned through the length of the cylinder so  
12 as to provide heat or remove heat as required by a particular reaction zone. Within such  
13 an illustrative embodiment, the plurality of catalysts includes autothermal reforming  
14 catalyst, desulfurization catalyst, water gas shift catalyst, preferential oxidation catalyst,  
15 and mixtures and combinations of these and similar catalysts. In one preferred  
16 illustrative embodiment, the heat exchanger is not positioned within the autothermal  
17 reforming catalyst. The hydrocarbon fuel feed utilized in the illustrative fuel processor is  
18 preheated, preferably by passing through the heat exchanger prior to being introduced to  
19 the cylinder or alternatively by a fuel pre-heater located in a function upstream position  
20 from the autothermal reforming reaction zone. A wide variety of hydrocarbon fuels may  
21 be utilized, however, in one illustrative embodiment the hydrocarbon fuel is selected  
22 form natural gas, gasoline, diesel, fuel oil, propane, liquefied petroleum, methanol,  
23 ethanol or other similar and suitable hydrocarbons and mixtures of these. It is preferred  
24 in one illustrative embodiment that the cylinder is oriented substantially vertically with  
25 the outlet end of the cylinder being on top and the flow of reactants being generally  
26 upward from the inlet end to the outlet end.

27 One of skill in the art should also understand and appreciate that another  
28 illustrative embodiment of the present invention includes a compact fuel processor for  
29 converting a hydrocarbon fuel feed to hydrogen rich gas, that is composed of a reaction  
30 chamber; a plurality of predefined reaction zones within said reaction chamber, wherein  
31 each reaction zone is characterized by the chemical reaction that takes place within the

1 reaction zone.; and a heat exchanger having an inlet end and an outlet end, wherein the  
2 heat exchanger is positioned at least partially within the reaction chamber. In one such  
3 illustrative embodiment, a first reaction zone contains autothermal reforming catalyst, a  
4 second reaction zone contains desulfurization catalyst, a third reaction zone contains  
5 water gas shift catalyst, and a reaction zone module contains preferential oxidation  
6 catalyst. When considering such an illustrative embodiment, it is contemplated that the  
7 heat exchanger is not substantially positioned within the first reaction zone. The  
8 hydrocarbon fuel feed for one illustrative embodiment is preheated by passing through  
9 the heat exchanger prior to being introduced to the reaction chamber. Alternatively, the  
10 mixture of hydrocarbon fuel feed, air, and water is preheated by passing through the heat  
11 exchanger prior to being introduced to the first reaction zone. A wide variety of  
12 hydrocarbon fuels may be utilized, however, in one illustrative embodiment the  
13 hydrocarbon fuel is selected from natural gas, gasoline, diesel, fuel oil, propane, liquefied  
14 petroleum, methanol, ethanol or other similar and suitable hydrocarbons and mixtures of  
15 these. In one preferred and illustrative embodiment, the inlet end of the heat exchanger is  
16 at the fourth reaction zone and the outlet end is at the second reaction zone.

17 It should be appreciated a by one of skill in the art that each reaction zone of the  
18 plurality of reaction zones may contain one or more catalysts. In one such illustrative  
19 embodiment, the catalysts are selected from autothermal reforming catalyst,  
20 desulfurization catalyst, water gas shift catalyst, preferential oxidation catalyst as well as  
21 mixtures and combinations of these and similar catalysts. Any particular reaction zone  
22 containing more than one catalyst may be separated from an adjacent reaction zone by a  
23 permeable plate that also serves to support the adjacent reaction zones. In one illustrative  
24 embodiment, the plate is selected from perforated metal, metal screen, metal mesh,  
25 sintered metal, porous ceramic, or combinations of these materials and similar materials.  
26 It is preferred within such an illustrative embodiment that the plate be at least partially  
27 composed of inconel, carbon steel, and stainless steel.

28 While the apparatus, compositions and methods of this invention have been  
29 described in terms of preferred or illustrative embodiments, it will be apparent to those of  
30 skill in the art that variations may be applied to the process described herein without  
31 departing from the concept and scope of the invention. All such similar substitutes and



- 1 modifications apparent to those skilled in the art are deemed to be within the scope and
- 2 concept of the invention as it is set out in the following claims.